Sterile Neutrinos As Subdominant Warm Dark Matter

Daniel Cumberbatch

Beecroft Institute for Particle Astrophysics & Cosmology

Oxford University

A. Palazzo, **D. Cumberbatch**, A. Slosar and J. Silk, arXiv:0707.1495

Outline

- Introduction
  - Neutrinos and the ***Dark Sector*** of the Universe
  - The properties of sterile neutrinos
  - Motivations for sterile neutrino dark matter
- Experimental constraints on sterile neutrino dark matter
  - Constraints from observations of **X-ray sources**
  - Constraints from high redshift measurements of the **Lyman-α forest**
- Experimental constraints on *sub-dominant* sterile neutrino dark matter
  - Constraints from the *HEAO-1* measurements of the **diffuse X-ray background**
  - Constraints from the *SDSS* measurements of the **Lyman- α forest**
- Theoretical predictions **Vs.** Experimental constraints
  - Treatment of theoretical uncertainties associated with hadronic interactions during the QCD epoch
  - Determination of upper limits on the fraction f_s of dark matter in the form of sterile neutrinos.
- Summary

Neutrinos and the Dark sector

- There are many candidates for dark matter (e.g. SUSY particles, Long-lived hadronically-decaying particles, Compact Composite Objects).
- The only *confirmed* particle candidate is the *hot* SM neutrino (decouples from thermal background at ~1 MeV).
- However, measurements of the power spectra of the distribution of galaxies and CMB anisotropies yield the stringent constraint $\Omega_\nu h^2 < 0.0067$.
- Independent measurements of flavour oscillations of Solar (e.g. *SNO*), Atmospheric (e.g. *Super-K*) and Reactor-based neutrinos (e.g. *KamLAND*) require **MASSIVE** neutrinos with

$$\Delta(m_{12}^2)_{SNO} \approx 7\text{x}10^{-5}\ \text{eV}^2,\ \Delta(m_{23}^2)_{SK} \approx 3\text{x}10^{-3}\ \text{eV}^2,\ \Delta(m_{12}^2)_{KLD} \approx 7\text{x}10^{-5}\ \text{eV}^2$$

- Particle physics beyond the standard model permits massive neutrinos aswell as the existence of (right-handed) *sterile neutrinos*.
- Sterile neutrinos possessing **keV** masses would be viable dark matter candidates.

What are Sterile Neutrinos?

- SU(3)xSU(2)xU(1) gauge singlet (Pontecorvo, 1967)
- "Sterile" - interacts only via weak mixing with "active" ν states
- νMSM (MSM+3 sterile ν) may explain m_ν~eV, $B\neq 0$ and dark matter

$$L_{\upsilon MSM} = L_{SM} + i\overline{N}^I (i\partial_\mu \gamma^\mu) N_I - \left(\overline{L}_\alpha M^D_{\alpha I} N_I + \frac{1}{2} M_I \overline{N}^c_I N_I \right) + h.c.$$

- Unlike see-saw mechanism, small Yukawa couplings, $F_{\alpha I}$, ($M^D_{\alpha I}=F_{\alpha I}\langle H\rangle$) give rise to small m_ν to explain their oscillations
- Small $F_{\alpha I}$ also crucial for baryogenesis and to assure that $\tau_1 \sim H_0^{-1}$
- The actual origin of $F_{\alpha I}$, and hence M_I, are unknown
- Exponentially suppressed $F_{\alpha I}$ originate in theories of extra dimensions.

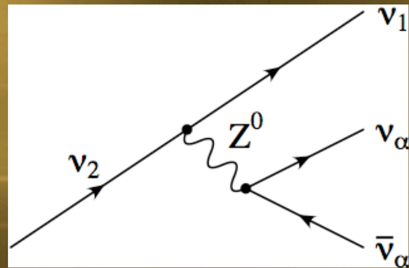
- Sterile ν have a variety of **production mechanisms** …

ν_s Production Mechanisms

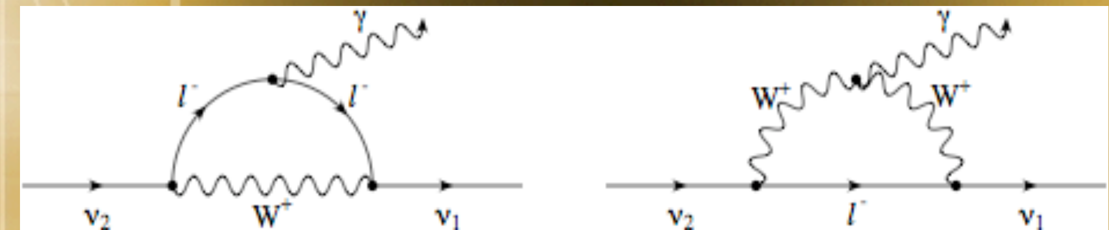
- Non-resonant oscillations
  - Generated through ν_a-ν_s oscillations involving off-diagonal elements of mixing matrix, predominantly at $T_{max.} \approx 133(m_s/1\text{keV})^{1/3}$ MeV
  - Small mixing angles ensure non-equilibrium ⇒ low densities
  - Don't require $L \neq 0$
  - Simplest model: Dodelson-Widrow (DW) mechanism
    - Standard thermal history
    - No additional couplings
    - Produces minimal relic density (few exceptions, see below)
  - Alternatives to DW mechanism
    - Entropy Dilution - massive particle decay following neutrino production
    - Additional Couplings (e.g. to SUSY particles, Inflaton, Higgs Singlet)
    - Low T_R cosmologies - production suppressed for $T_R < T_{max.}$
- Resonant Oscillations
  - Non-thermal Sterile Neutrinos
    - $L \neq 0$ drives MSW resonant conversion process
    - Favours low energy neutrinos ⇒ **'Cool'** Sterile Neutrinos
    - Limits from free-streaming effects relaxed

Decay modes

- *Dominant* decay to **3 active neutrinos** ($\nu_s \rightarrow 3\nu_a$)



- *Loop-suppressed* **radiative** decay ($\nu_s \rightarrow \gamma\, \nu_a$)



$$\Gamma_s = \frac{9\alpha}{256\cdot 4\pi^4}\sin^2(2\vartheta_s)m_s^5 \approx 1.38\times 10^{-22}\sin^2(2\vartheta_s)\left(\frac{m_s}{1\mathrm{keV}}\right)^5 s^{-1}$$

(Barger et al., Pal & Wolfenstein)

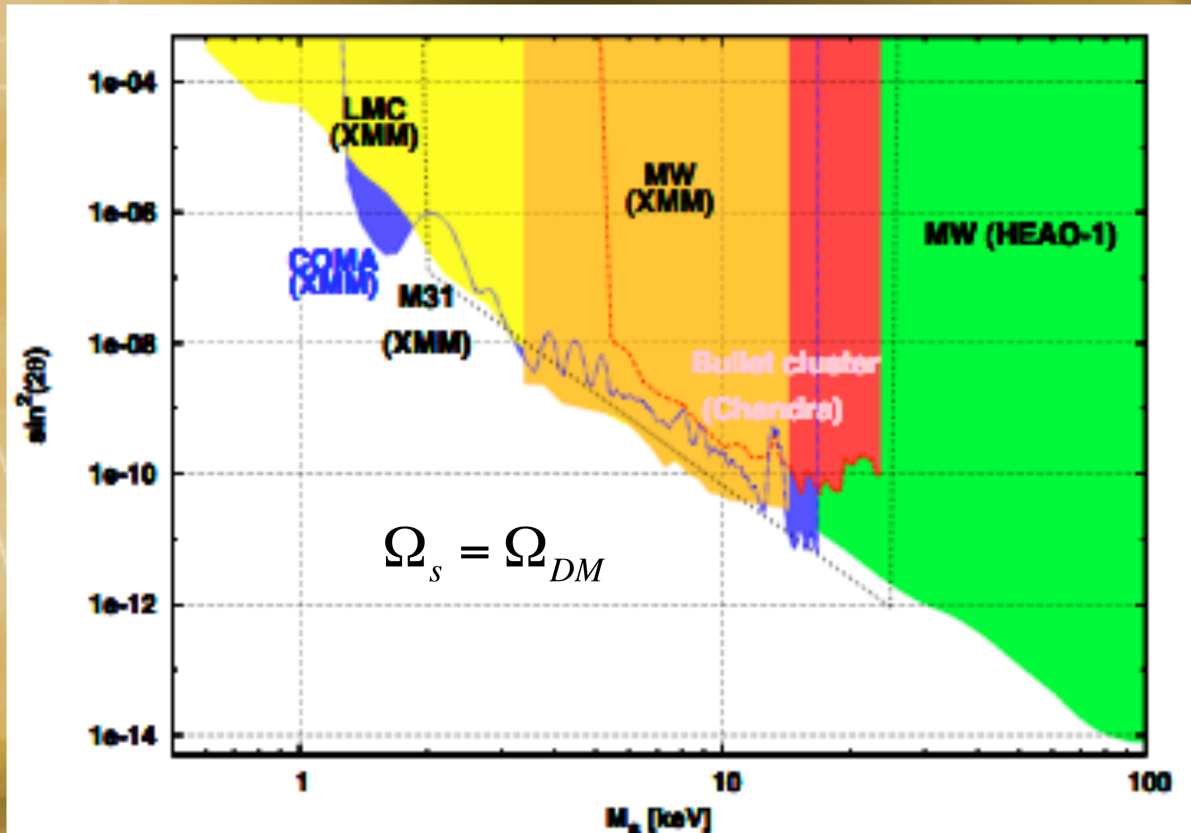
- Photon Energy $E_\gamma=(m_s^2-m_a^2)/2m_s \approx m_s/2$ for $m_s \gg m_a$
- For $m_s \sim 1$keV $\Rightarrow$ **X-rays**
- Use X-ray observations to constrain m_s and $\sin^2(2\theta_s)$ (and later, f_s) for keV SN DM

Motivations for keV SN DM

- Resolution to inconsistencies from ΛCDM halo simulations
  - Overproduction of small scale matter structures in galaxy distribution
  - Central cores in low-mass galaxies (Dalcanton & Hogan)
  - Overpopulation of small-scale satellites (Kauffman et al., Klypin et al.)
- Contribution to unresolved diffuse X-ray background (Abazajian et al.)
- Facilitates HI production/star formation $\Rightarrow$ Early Reionisation (Mapelli et al., Biermann & Kusenko)
- Pulsar "kick" velocities (Kusenko & Segre, Fuller et al.)
- Re-generation of Supernova shockwaves (Hidaka and Fuller)
- Formation of early SMBH ($10^9 M_\odot$ at $z \approx 6.5$) (Munyaneza & Biermann)
- Baryon asymmetry (Asaka)

Experimental constraints on m_s and $\sin^2(2\vartheta_s)$

- X-rays (Clusters, dSphs, MW, Galaxies, XRB)

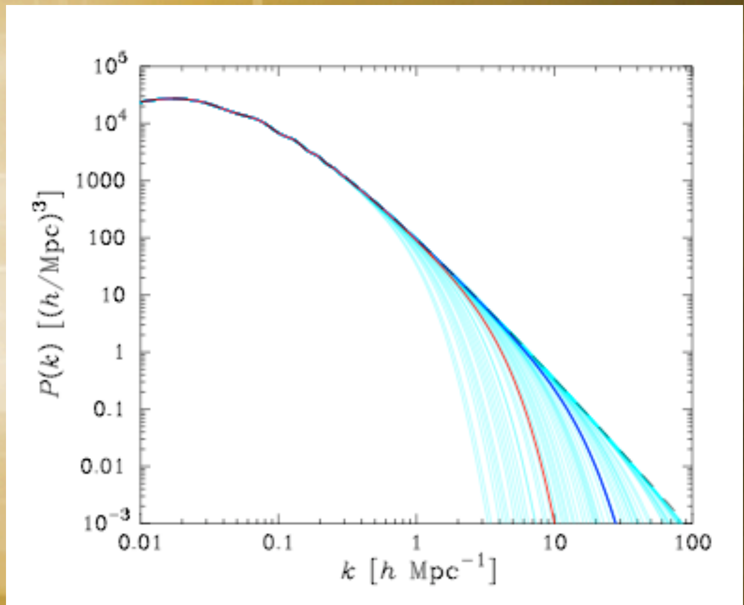


(Ruchayskiy, arXiv:0704.3215)

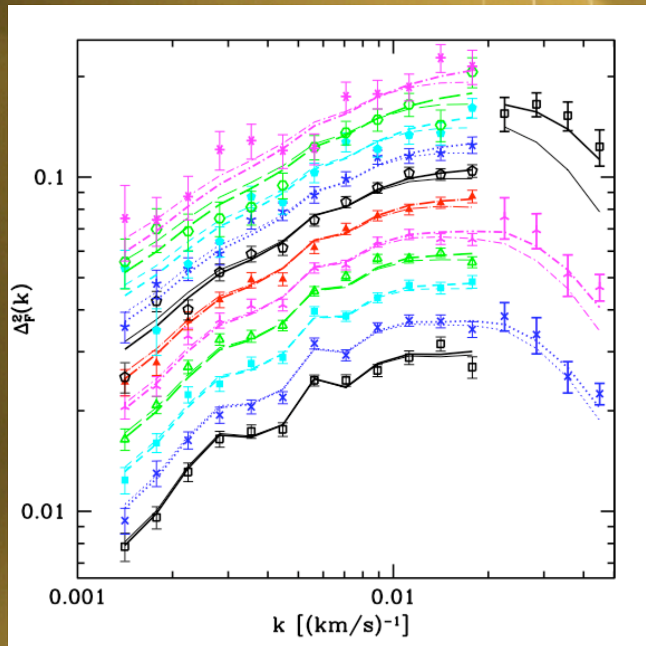
- All these sources have similar orders of N_H and L but different thermal emissions
- F.O.V. and Energy resolution of instruments dictate sensitivity

Experimental constraints on m_s and $\sin^2(2\vartheta_s)$

- ✦Lyman-α
  - ✦Sensitive to small-scale matter perturbations where SN are significant
  - ✦Operates at high-z before non-linear growth erases free-streaming effects



(Abazajian, astro-ph/0511630)



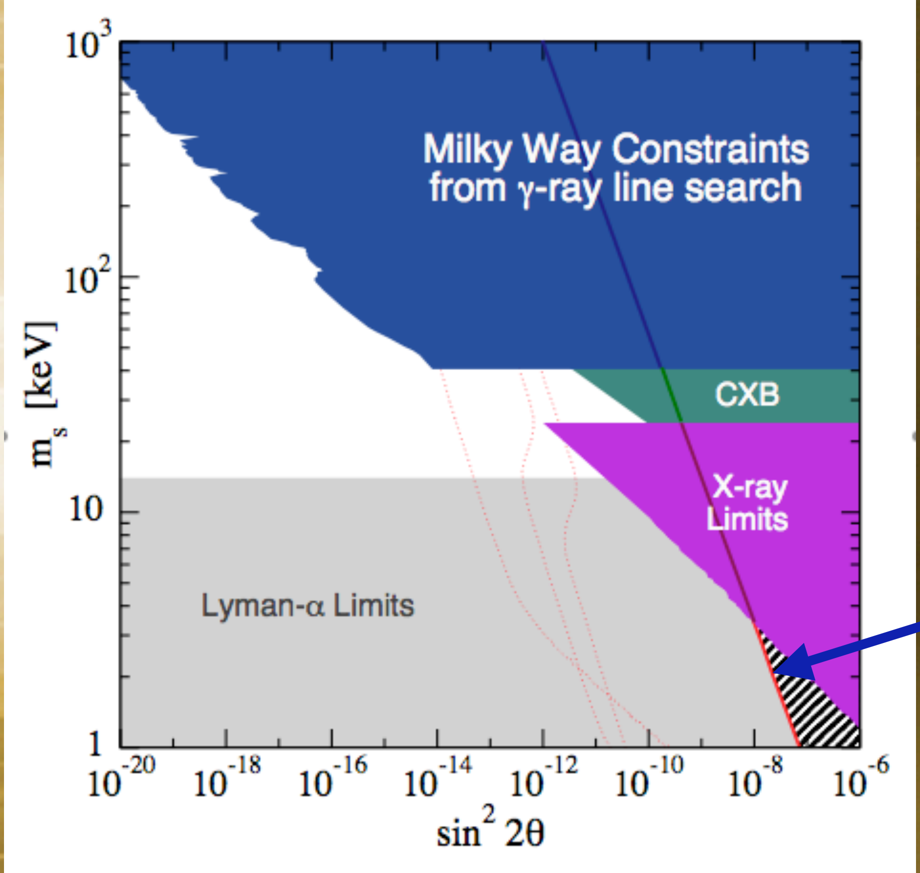
(Seljak et al., astro-ph/0602430)

✦⇒ m_s >14 keV includes 10% suppression from non-thermal nature of SN

✦Recent calculations imply $\langle p_s\rangle/\langle p_a\rangle$ can be as low as 0.8

⇒m_s>11.5 keV ($\langle p_s\rangle/\langle p_a\rangle \sim 0.8$)

Is Dodelson-Widrow SN DM still permitted?



(Yuskel et al., arXiv:0706.4084)

$$f_s = \frac{\Omega_s}{\Omega_{DM}}$$

DW SN DM for f_s=1 (Ω_{DM}=0.24)

If f_s=1 is excluded, how large can f_s be?

Spectral Analysis of HEAO-1 XRB data

- Fit *HEAO-1* data to a prescribed power-law model (Gruber et al.)

$$\varphi_E^{Gruber} \equiv \frac{d^2 F_E^{\mathrm{Gruber}}}{d\Omega dE} = C_{\mathrm{XRB}} \exp\left(-\frac{E}{T_{\mathrm{XRB}}}\right)\left[\frac{E}{60\ \mathrm{keV}}\right]^{-\Gamma_{\mathrm{XRB}}+1} \mathrm{sr}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

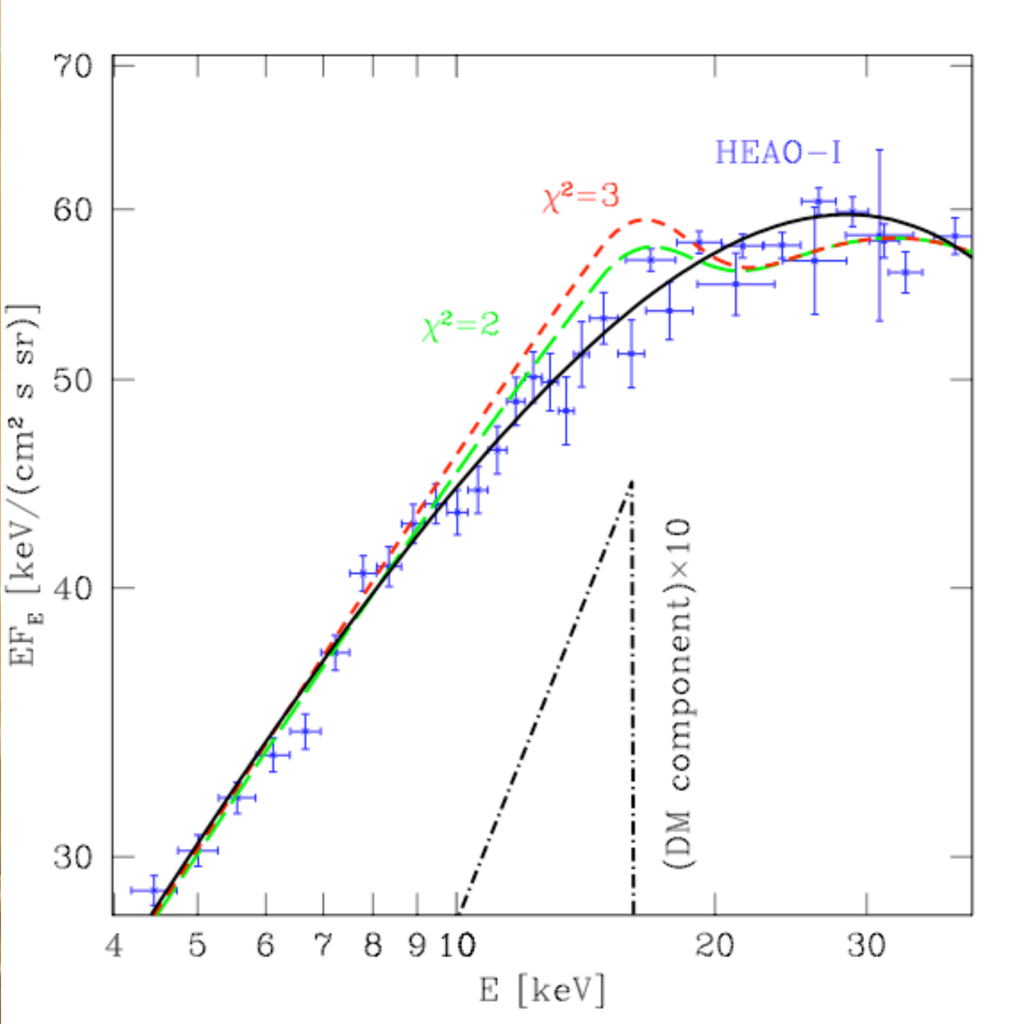
  (Such a spectrum could potentially be generated by a population of obscured AGN)

- Add MW and extragalactic (EG) contributions from SN DM (for given m_s), correcting for finite energy resolution of *HEAO-1* ($\Delta E/E \sim 0.25$)

- Vary C_{XRB}, T_{XRB}, Γ_{XRB} and $\sin^2(2\theta_s)$ until χ^2 *worsens* by $\Delta\chi^2$ corresponding to a 3σ C.L.

- Determine $\sin^2(2\theta_s)$ for all m_s within range of data

Spectral Analysis of HEAO-1 XRB data



(Boyarsky et al., astro-ph/0512509)

EG and MW flux from SN DM

- Extragalactic differential energy flux

$$\varphi_E^{\mathrm{EG}} \equiv \frac{d^2F_E^{\mathrm{EG}}}{d\Omega dE} = f_s \frac{\Gamma_\gamma}{4\pi m_s} \frac{\Omega_{\mathrm{dm}}\rho_c}{H(\{m_s/2E\}-1)}$$

  - Flat, Λ-matter dominated Universe ($\Omega_{\mathrm{dm}} \approx 0.21$)

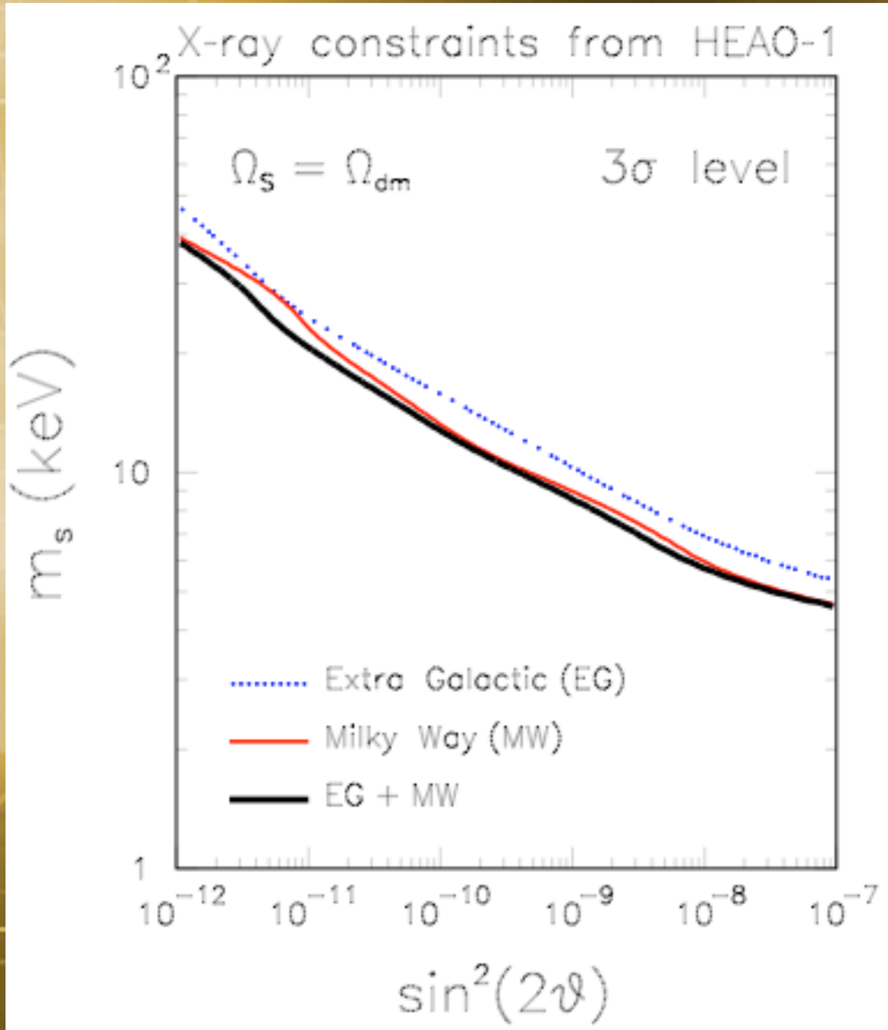
$$H(z) \approx H_0\sqrt{\Omega_\Lambda + \Omega_{\mathrm{m}}(1+z)^3},\ (\Omega_{\mathrm{m}} \approx 0.26,\ \Omega_\Lambda \approx 0.74, H_0 \approx 73\ \mathrm{km\ s^{-1}\ Mpc^{-1}})$$

- Local differential energy flux from MW

$$\varphi_E^{\mathrm{MW}} \equiv \frac{d^2F_E^{\mathrm{MW}}}{d\Omega dE} = f_s \frac{\Gamma_\gamma}{4\pi m_s} \int_{\mathrm{l.o.s.}} \rho_{\mathrm{dm}}(x,\phi)dx \equiv f_s \frac{\Gamma_\gamma}{4\pi m_s} S_{\mathrm{dm}}(\phi)$$

$$\Rightarrow R = \frac{\int \varphi_E^{\mathrm{MW}} dE}{\int \varphi_E^{\mathrm{EG}} dE} \approx 0.7\left(\frac{S_{\mathrm{dm}}(\phi)}{0.01\ \mathrm{g\ cm^{-2}}}\right) \sim 1 \text{ for typical profiles (away from GC)}$$

X-ray constraints on m_s and $\sin^2(2\vartheta_s)$



$$\Gamma_s \propto f_s\, m_s\, \sin^2(2\vartheta_s)$$

For f_s<1 we expect a "rigid" shift in constraints to larger $\sin^2(2\theta_s)$ by $1/f_s$

Ly-α constraints on m_s and $\sin^2(2\vartheta_s)$ ($f_s<1$)

- $m_s>11.5$ keV ($f_s=1$) from limiting suppression of $P(k)$ for $k>\sim 1\text{Mpc}^{-1}$
- For $f_s<1$ its most appropriate to run a grid of hydrodynamical simulations involving WDM+CDM and relate Ly-α power spectrum to parameters.
- Alternatively, we can obtain reliable constraints by "rescaling" $f_s=1$ results
- Using CAMB (Lewis et al.), we grow perturbations in a WDM(f_s)+CDM(1-f_s) scenario using a SN relic abundance of

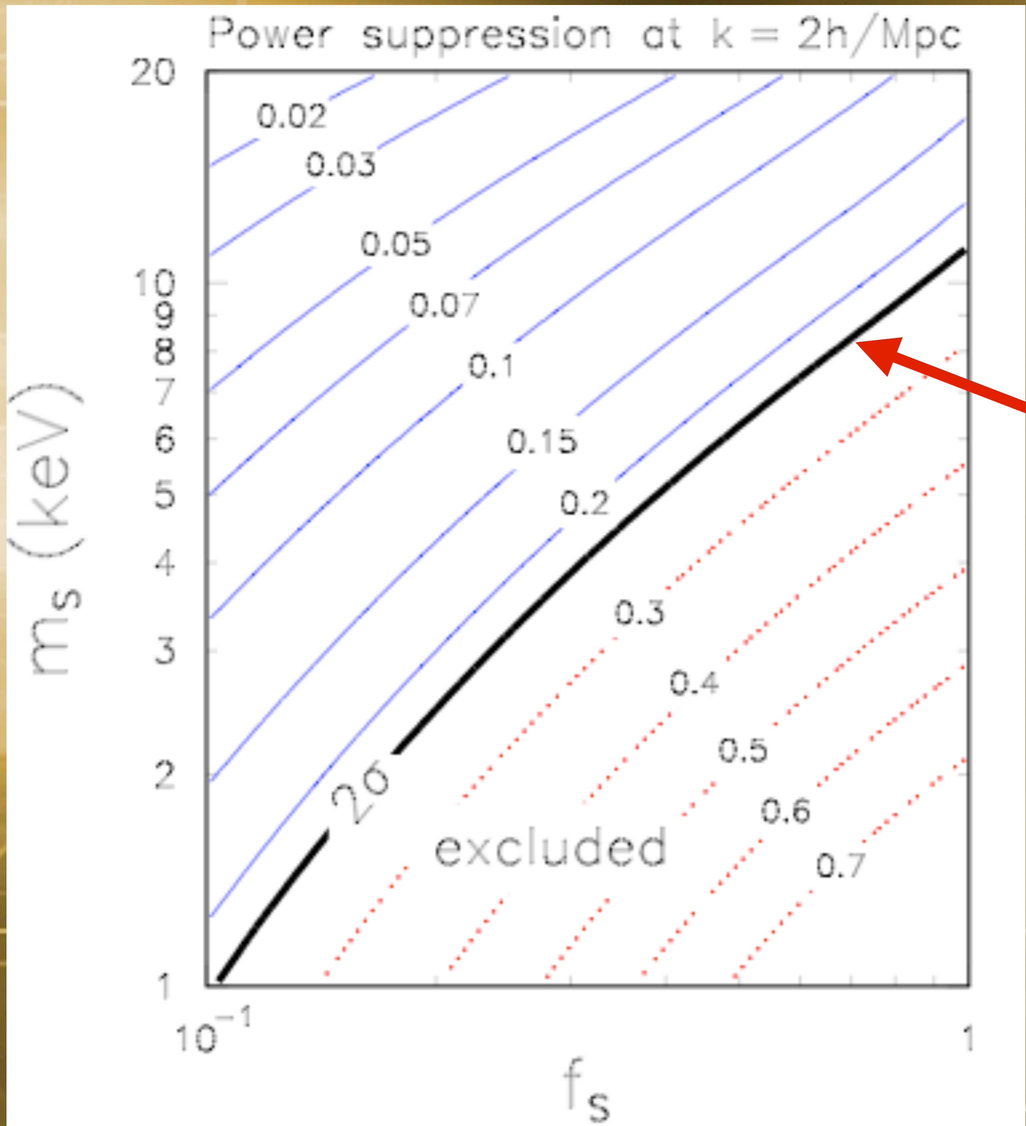
$$\Omega_s h^2 = \beta\left(\frac{m_s}{93.2\text{eV}}\right)$$

- Owing to "pencil-beam" nature of Ly-α measurements we use $P_{1D}(k)$

$$P_{1\text{D}}(k) = \frac{1}{2\pi}\int_k^\infty P_{3\text{D}}(k)kdk$$

- Determine $(m_s)_{\text{min.}}$, for $f_s<1$, by invoking $P_{1D}(k_f, f_s<1)=P_{1D}(k_f, f_s=1)$ at $k_f\sim 2h$ Mpc^{-1}, where *SDSS* Ly-α data is most sensitive.
- Reliable results for $f_s>0.1$ for $1<k_f/(h\ \text{Mpc}^{-1})<5$ (<10% variation).z

Ly-α constraints on m_s and $\sin^2(2\vartheta_s)$ (f_s<1)



$P(k_f,f_s)\sim(1\text{-}0.23)P_{CDM}(k_f,f_s=1)$

Theoretical uncertainties

- SN which are non-resonantly produced have a relic abundance (Asaka et al.)

$$\Omega_s h^2 = 0.275\, F(m_s, \vartheta_\alpha^{a=e,\mu,\tau}) \left(\frac{m_s}{1\mathrm{keV}}\right)^2 \left(\frac{\sin^2(2\vartheta)}{10^{-7}}\right)$$

- Accounting for hadronic uncertainties during QCD epoch, best-fit relation between f_s, m_s and $\sin^2(2\theta_s)$ is

$$\log_{10}(f_s^{\mathrm{av.}}) = 0.20 + 1.84 \log_{10}\left(\frac{m_s}{1\mathrm{keV}}\right) + \log_{10}\left(\frac{\sin^2(2\vartheta_s)}{10^{-7}}\right)$$

- Pushing all errors in the same direction, one either obtains the minimal…

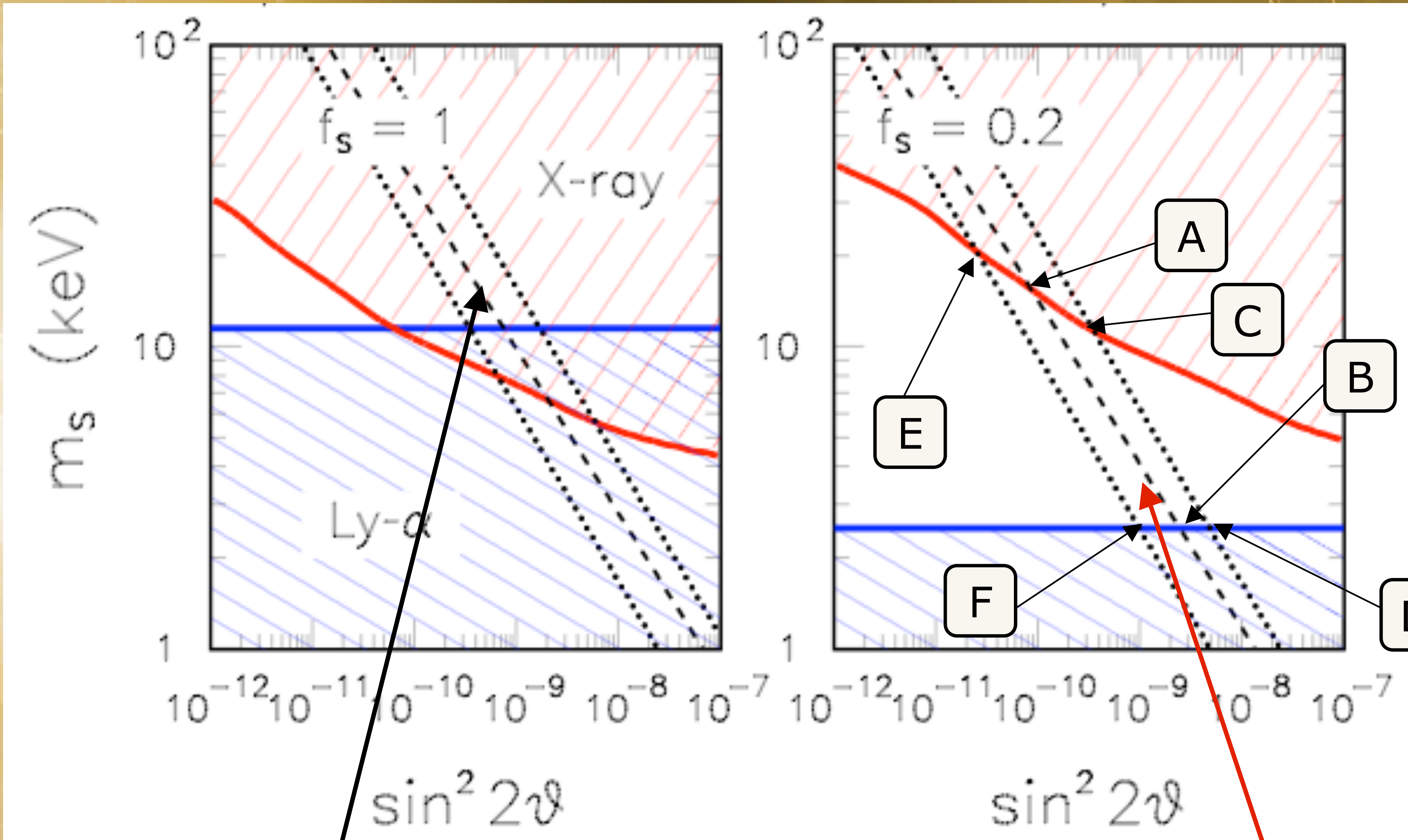
$$\log_{10}(f_s^{\mathrm{min.}}) = -0.07 + 1.74 \log_{10}\left(\frac{m_s}{1\mathrm{keV}}\right) + \log_{10}\left(\frac{\sin^2(2\vartheta_s)}{10^{-7}}\right)$$

…or the maximal abundances

$$\log_{10}(f_s^{\mathrm{max.}}) = 0.62 + 1.74 \log_{10}\left(\frac{m_s}{1\mathrm{keV}}\right) + \log_{10}\left(\frac{\sin^2(2\vartheta_s)}{10^{-7}}\right)$$

- We conservatively consider these extreme cases to represent a 2σ C.L.

Experimental constraints & Theoretical predictions (2σ)



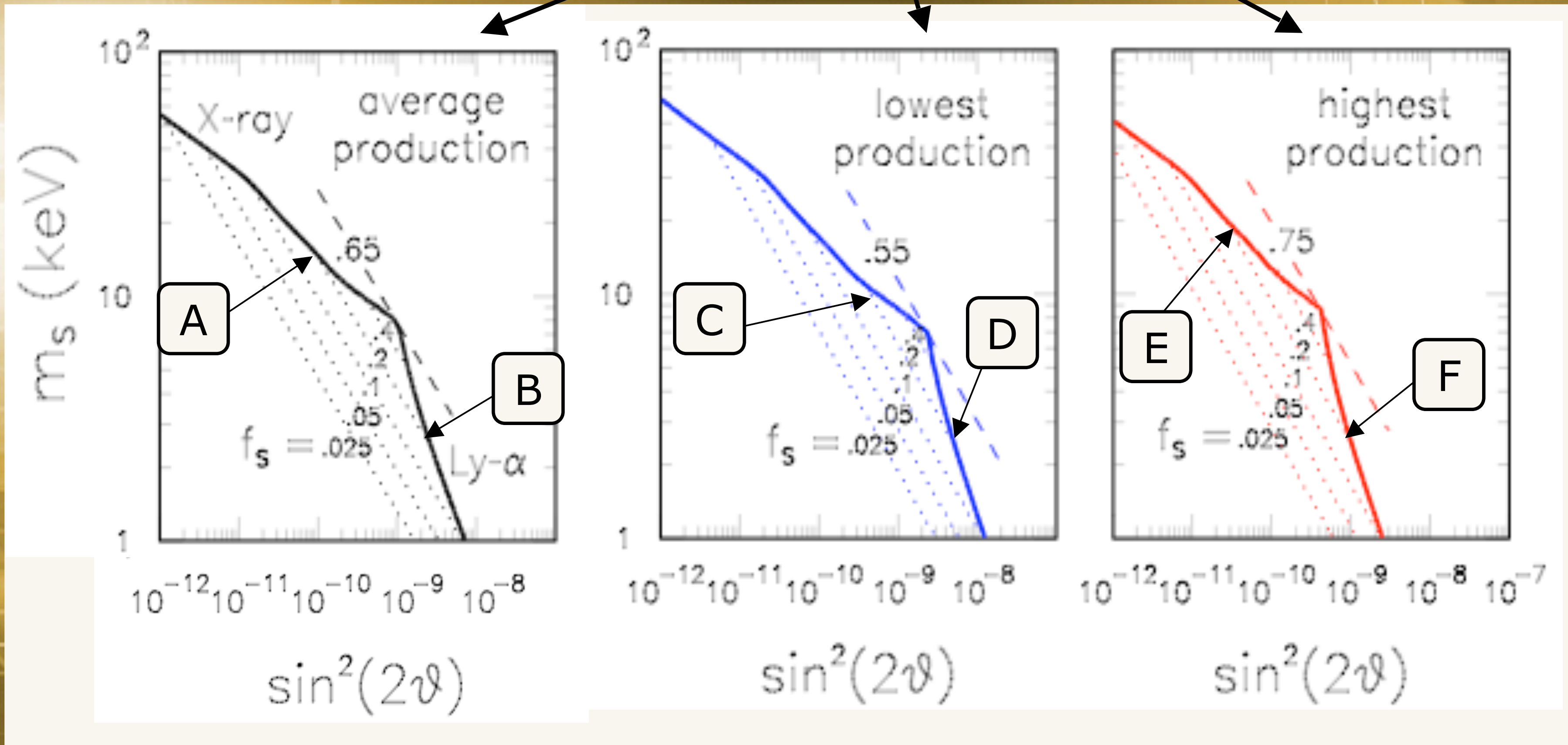
DW SN DM excluded for f_s=1

DW SN DM permitted for f_s=0.2

($2.5 < m_s/1\text{keV} < 16$, $10^{-10} < \sin^2(2\theta_s) < 2.5\times10^{-9}$)

Constraints on the DW scenario (2σ)

✦ Plot corresponding points (A,B), (C,D) and (E,F) for all $f_s<1$



$\Rightarrow 0.55<(f_s)_{max.}<0.75$

Theoretical uncertainties (Quantitative treatment)

- Vary f_s around $f_s^{av.}$ given by best-fit formula.
- Adopt a normal distribution of $\log_{10}(f_s)$ with a s.d. equal to half the excursion, determined by extreme formulae.
- This corresponds to adding a penalty factor η to the *total* χ^2

$$\chi^2 = \chi^2_{\text{X-ray}}(\sin^2(2\vartheta_s, m_s, f_s) + \chi^2_{\text{Ly-}\alpha}(m_s, f_s) + \eta(\sin^2(2\vartheta_s, m_s, f_s)$$

$$\eta(\sin^2(2\vartheta_s, m_s, f_s) = \left(\frac{\log_{10}(f_s) - \log_{10}(f_s^{\text{av.}})}{\Delta \log_{10}(f_s)}\right)^2$$

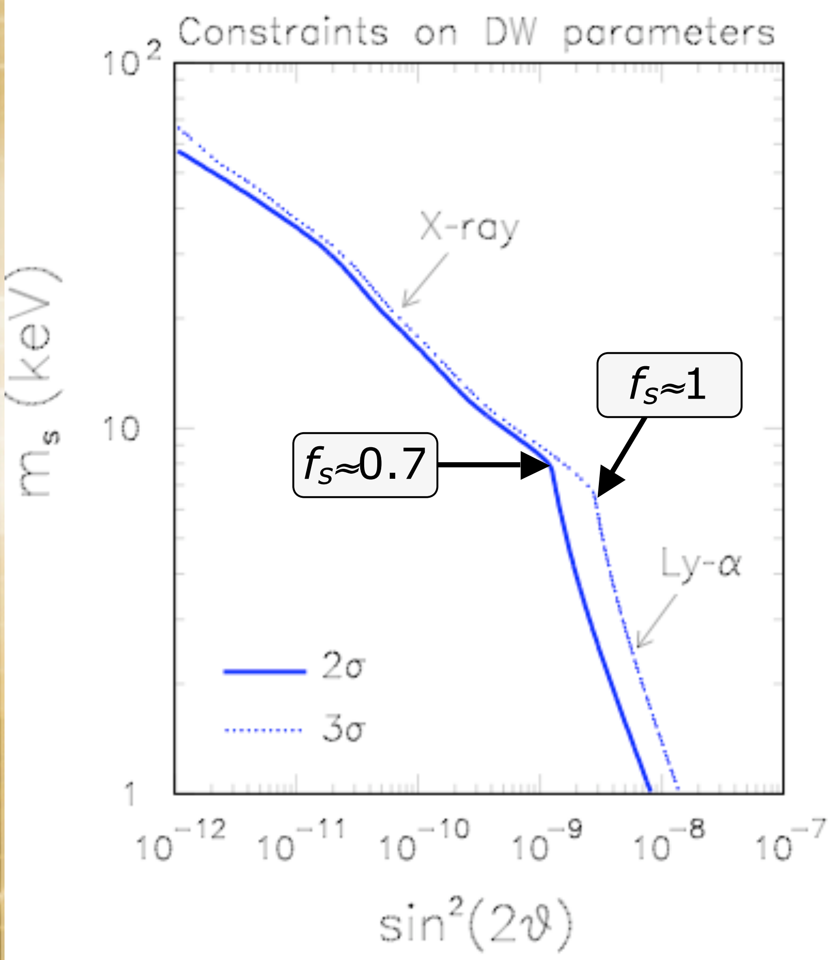
with 1σ (asymmetric) errors

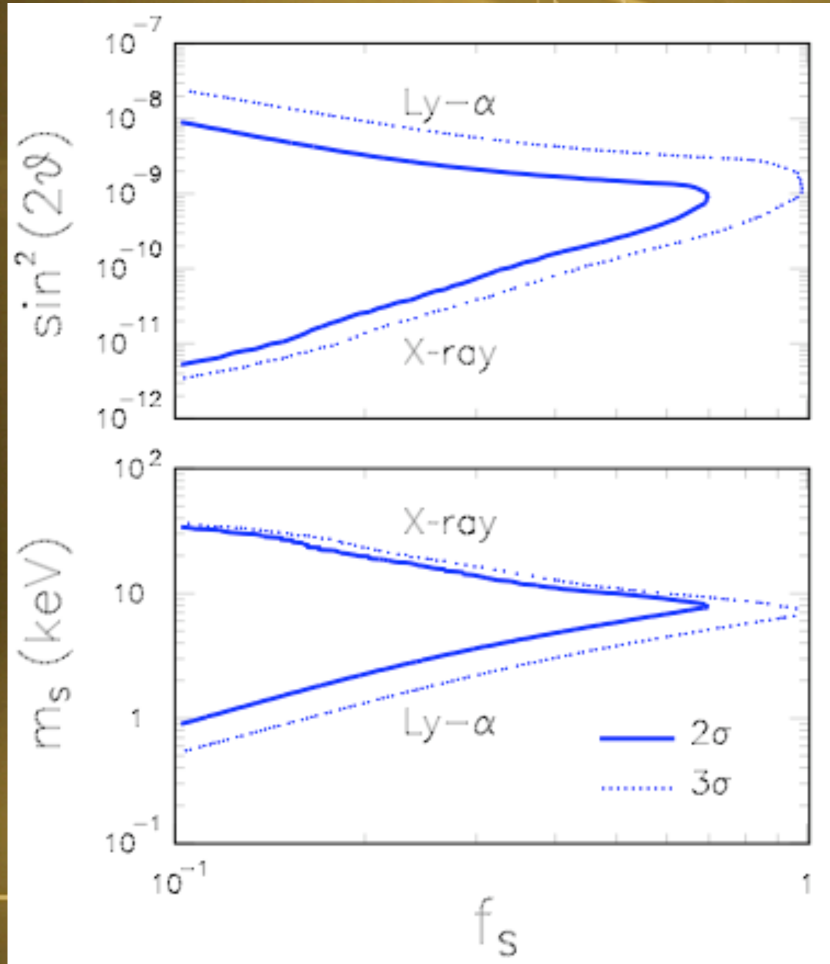
$$\Delta \log_{10}(f_s) = 0.5\left[\log_{10}(f_s^{\text{max.}}) - \log_{10}(f_s^{\text{av.}})\right] \quad (f_s > f_s^{\text{av.}})$$

$$\Delta \log_{10}(f_s) = 0.5\left[\log_{10}(f_s^{\text{av.}}) - \log_{10}(f_s^{\text{min.}})\right] \quad (f_s < f_s^{\text{av.}})$$

- Marginalising χ^2 wrt f_s (or m_s or $\sin^2(2\theta_s)$), we obtain new constraints…

Constraints on the DW scenario





⇒ $(f_s)_{max.}$≈0.7 (2σ), $(f_s)_{max.}$=1 (~3σ)

Summary & Conclusions

- Recent results disfavour keV dominant sterile neutrino dark matter produced via the Dodelson-Widrow mechanism.
- Relaxing the presumption that $\Omega_s=\Omega_{dm}$, we have shown how X-ray and Ly-α constraints can be re-interpreted for $\Omega_s<\Omega_{dm}$.
- We have shown how current data provides a conservative upper bound on the fraction f_s of DW SN DM, and limits on m_s and $\sin^2(2\theta_s)$ for a given $\sim 0.1<f_s<(f_s)_{max}$.
- We obtained the limits $f_s<\sim 0.7$ (2σ), with $f_s=1$ rejected at $\sim 3\sigma$.
- More sensitive X-ray observations, a better understanding of the systematics in Ly-α measurements and a reduction in the theoretical uncertainties all have a crucial role in improving our results.